JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
Vol. 44, No. 2 AMERICAN WATER RESOURCES ASSOCIATION April 2008

A REVIEW OF WATER LEVEL FLUCTUATIONS ON AQUATIC BIOTA WITH AN EMPHASIS ON FISHES IN ICE-COVERED LAKES[1]

Peter A. Cott, Paul K. Sibley, W. Murray Somers, Michael R. Lilly, and Andrew M. Gordon[2]

ABSTRACT: The effects of water level fluctuations on fish and other aquatic biota, with an emphasis on winter water withdrawal in northern regions is reviewed. Water demands for population growth and development are adding pressure on water reserves, particularly when coupled with changing climatic conditions. Water level fluctuations can have adverse effects on the environment, most notably to hydrologic and biotic processes ranging in magnitude from the micro-scale to landscape level. Water level management of lakes and reservoirs can affect all forms of aquatic biota. The severity of effect is dependant on the magnitude, duration and timing of the fluctuation, and the species exposed. In northwestern Canada and northern Alaska, water is withdrawn from water bodies to construct ice-roads and other winter based developments. Biota in small, isolated water bodies are particularly sensitive to reductions in winter water levels. Water withdrawals can reduce the oxygen available to overwintering fish, while reduced water levels can reduce habitat for fish and furbearers, and freeze littoral areas killing plants, invertebrates, and fish eggs. Regulatory winter water withdrawal thresholds have been developed in the Northwest Territories and Alaska and continue to be refined as new data becomes available. The use of thresholds can help minimize or avoid negative impacts to the environment, particularly fish, from winter water withdrawal activities. Many different factors may influence the effect that winter water withdrawal has on a water body, such as basin shape, substrate and location. More research is warranted to better understand the linkages between anthropogenic and natural water level fluctuations and their combined effect on aquatic ecosystems. A general decision support system is proposed for minimizing risk to aquatic life from winter water withdrawal activities.

(KEY TERMS: water withdrawal; ice roads; water level fluctuations; ice; lakes; northern resource development; water use; winterkill; aquatic biota.)

Cott, Peter A., Paul K. Sibley, W. Murray Somers, Michael R. Lilly, and Andrew M. Gordon, 2008. A Review of Water Level Fluctuations on Aquatic Biota With an Emphasis on Fishes in Ice-Covered Lakes. *Journal of the American Water Resources Association* (JAWRA) 44(2):343-359. DOI: 10.1111/j.1752-1688.2007.00166.x

INTRODUCTION

There are immense freshwater reserves in Canada and Alaska. Due to the abundance of this resource, it is often only in times of regional water shortages or serious contamination events that we are reminded of the complacency with which we view our water resources (Ritter *et al.*, 2001). However, this attitude is changing, as evidenced by the recurring debates in

[1]Paper No. J06143 of the *Journal of the American Water Resources Association* (JAWRA). Received October 17, 2006; accepted September 13, 2007. **Discussions are open until October 1, 2008**.

[2]Respectively (Cott and Somers), Department of Fisheries and Oceans, Yellowknife, Northwest Territories, Canada X1A 1E2; (Cott, Sibley, Gordon) Department of Environmental Biology, University of Guelph, Guelph, Ontario, Canada N1G 2W1; and (Lilly) GW Scientific, Fairbanks, Alaska 99708 (E-Mail/Cott: pete.cott@dfo-mpo.gc.ca).

recent years about freshwater export policies from Canada to the United States and other countries. As the threat of water scarcity grows imminent, North American society will begin to realize the value of water as an essential commodity, necessary to sustain the lifestyles to which we have grown accustomed.

Of the estimated 1.4 billion cubic kilometers of water on the planet, less than 1% is available as freshwater (Brown, 2002). Pollution further reduces the availability of freshwater resources by making some water sources unfit for human use (Johnson *et al.*, 2001; Ritter *et al.*, 2001). As human populations continue to grow and gravitate towards hyper-consumptive lifestyles, water and water-generated power are becoming more valuable and the construction of new reservoirs are becoming more economically attractive (Avakyan and Podol'skii, 2002; Coops *et al.*, 2003). The increasing draw from ground and surface water sources can significantly alter flow in streams and rivers, changing the hydraulic regime over large geographical regions.

Anthropogenic disturbances can alter natural hydrologic cycles causing extreme water level fluctuations that can surpass the physiological or behavioral adaptability of many organisms (Coops *et al.*, 2003). Small inland lakes are particularly vulnerable to changes in water inputs, because any disturbance from land-use activities can impact the entire lake ecosystem (Evans, 2005). The impacts of water level fluctuation in shallow lakes are not well understood. Lakes respond to water level fluctuations in a nonlinear fashion and as a result, the impacts of these fluctuations are difficult to predict (Coops *et al.*, 2003).

Climate has a dramatic effect on hydrology at both local and regional scales. Water levels in lakes and rivers function within a normal range with naturally occurring climatic induced variations. The range of this fluctuation can be drastically altered due to anthropogenic water use and climate change, which can impact the natural function of shallow lakes (Coops *et al.*, 2003). Flooding or drought can influence processes on a micro-climate scale, resulting in soil slumping, shifts in permafrost, and atmospheric relative humidity, which may change the structure of the ecosystem. These effects can be induced or exacerbated because of water regulation (Avakyan and Podol'skii, 2002). Climate change may also have serious repercussions for aquatic systems in boreal landscapes. Using climate change models, Stefan *et al.* (2001) predicted that shorter winters and ice-covered periods may greatly reduce the incidences of fish winterkill. In northwestern Canada, the opposite effect may occur, where climate change is predicted to reduce precipitation, which would reduce ground water and stream inflows into lakes during the winter and may increase the potential for fish mortality through reduced oxygen concentrations (Danylchuk and Tonn, 2003). A reduction in precipitation could also result in reduced water levels and cause impacts to fishes by reducing available shoreline habitat that is critical to spawning and foraging. From analysis of satellite imagery it has been suggested that approximately 11% of lakes in areas of discontinuous permafrost have become shallower or have disappeared within the last 30 years (Smith *et al.*, 2005a). Smith *et al.* (2005a) and Hinzman *et al.* (2005) suspected that increasing temperatures over this period may have initiated thawing of permafrost, which influences local water tables.

It is estimated that there are three to four million lakes in the boreal regions of North America and Eurasia (Schindler, 1998). Biota confined to small inland lakes is particularly vulnerable to water level perturbations during periods of ice cover. With ice cover, oxygen inputs are minimal or nonexistent, oxygen reserves deplete with biological demands, and often inlets and outlets freeze or have reduced flows making escape from an undesirable environment impossible (Jansen, 2000; Coops *et al.*, 2003; Evans, 2005). In northern regions water withdrawal from small lakes for the construction of winter roads and other ice-based infrastructure can further diminish oxygen and water level conditions and may impact the aquatic biota within. Understanding the effects of combined natural and anthropogenic activities on specific aquatic environments is critical to the sustainability of these systems.

In this paper, the effects of water level fluctuations on fishes and other aquatic biota is reviewed, with a detailed discussion on winter water withdrawal in the northwestern regions of Canada and in northern Alaska. Knowledge of the consequences of winter water withdrawals on aquatic biota is essential for the development of strategies to minimize, mitigate, or avoid harmful impacts. This paper is not an exhaustive review of all literature on water level fluctuations and withdrawals, but rather an overview of the issues and potential impacts to aquatic and semi-aquatic biota, with particular emphasis on fishes.

WATER LEVEL FLUCTUATION EFFECTS AT THE LANDSCAPE LEVEL

Investigations into the potential impacts of water level fluctuations on aquatic ecosystems have been conducted for decades, most notably in relation to the damming of rivers for hydroelectric power generation and flood control (Hecky *et al.*, 1984; Rosenberg *et al.*, 1987; Avakyan and Podol'skii, 2002). Water fluctuations from hydroelectric power generation have been shown to affect aquatic plant communities (Rørslett, 1989; Hellsten *et al.*, 1996; Hudon, 2004; Turner *et al.*, 2005), aquatic invertebrates (Hunt and Jones, 1972; Benson and Hudson, 1975), fishes (Alexander, 1986; Jansen, 2000; Rose, 2005), and terrestrial plants and animals (Townsend, 1975). A notorious example is the Bennett Dam in northwestern Canada. Built in 1967, it has had tremendous impacts on the Peace-Athabasca Delta ecosystem (Rosenberg *et al.*, 1987). The creation of the dam and the Williston Reservoir greatly reduced downstream flows, particularly during freshet, which previously backed up the waters of Lake Athabasca and resulted in the annual flooding of the Peace-Athabasca Delta. Without annual flooding, thousands of hectares of downstream marsh habitat have been lost. Lowered water levels exposed lake bottoms and the shorelines of marsh lakes were reduced by 40%. This had immediate negative effects on the delta ecosystem: less access by fish to spawning areas and reduced quality of over-wintering habitat, reduced waterfowl production through loss of nesting and molting habitat, massive reductions in muskrat (*Ondatra zibethicus*) and wood bison (*Bison bison*) habitat and populations, changes in riparian vegetation and successional pathways resulting in large willow (*Salix* sp.) populations, and a sharp decrease in subsistence and economic harvest of muskrat by the Chipewyan and Métis people in the settlement of Fort Chipewyan (Townsend, 1975; Rosenberg *et al.*, 1987).

The influences of dammed waterways can be large in scale, significantly changing the shape and function of aquatic ecosystems and landscapes (Rosenberg *et al.*, 1987). For instance, over one-third of the surface area of all Finnish water bodies is comprised of regulated systems (Alasaarela *et al.*, 1989 *in* Hellsten *et al.*, 1996). Large dams can impact hundreds of kilometers of downstream riparian and aquatic habitats through water level manipulation (Townsend, 1975; Johnson *et al.*, 2001), as well as flooding and impounding large areas of upstream habitat, effectively changing lotic systems into lentic systems. By limiting the extent of annual flooding, dams can change the fluvial geomorphology of downstream environments (Bonetto *et al.*, 1989). Riparian vegetation can be displaced by flood waters leading to changes in successional pathways that encourage early succession plant species. Lowered water levels can have the opposite effect by advancing successional stages (Townsend, 1975; Rosenberg *et al.*, 1987). Dams regulate and limit natural flood cycles, but can also increase the risk of catastrophic floods from potential dam failure (Bonetto *et al.*, 1989). Flood control and the construction of navigation channels can alter, and may destroy, riparian habitats and wetlands (Johnson *et al.*, 2001). Biota residing in affected habitats have differing levels of resilience. Animals with a lower capacity for dispersion, such as amphibians, usually experience a higher direct mortality rate than more mobile animals such as birds. Displacement of species can result in higher competition between species as suitable habitats are lost (Avakyan and Podol'skii, 2002).

Dams, other barriers, and water management activities are contributing factors that threaten 40% of Canada's endangered fish species (Rose, 2005). Biodiversity may either increase or decrease because of reservoir development, depending on the type of environment where the reservoir is located. Rare species, which tend to be habitat specific, often experience pronounced negative impacts compared with more common species that are habitat generalists (Avakyan and Podol'skii, 2002). Zoocomplexes are often reconstructed because of major shifts in habitat types and structure. This may happen well before the actual filling of a reservoir because of predevelopment impacts, such as intensive timber harvesting (Avakyan and Podol'skii, 2002).

Water level fluctuations associated with dams can also influence and alter biogeochemical processes in lakes. For example, flooding can extend into the littoral zone, inundating vegetation, thus resulting in substantial releases of methane gas (Juutinen *et al.*, 2001). Flooding can physically alter riparian areas by scouring banks, cutting new channels, and by redistributing organic matter, sediments, and aquatic animals (Rosenberg *et al.*, 1987; Bonetto *et al.*, 1989). Impacts such as these can change the concentrations of dissolved organic carbon (DOC), which affects numerous biogeochemical processes that control water quality (e.g., metal binding, speciation, bioavailability of contaminants, and nutrient cycling) in addition to altering light penetration into aquatic systems (Prowse *et al.*, 2001). Also, reservoirs created by dams act as nutrient sinks, depriving downstream habitats of nutrients such as phosphorus, or release nutrients in pulses that are less useful or even harmful to downstream environments (Bonetto *et al.*, 1989). In boreal environments, building reservoirs for hydroelectric power generation increase fluxes of DOC and mercury from the flooding of wetlands or terrestrial soils, often leading to higher concentrations of mercury in recipient biota (Rosenberg *et al.*, 1987; Schindler, 1998).

The way that dams are managed can have significant consequences on the local environment. Negative environmental consequences can be minimized by reducing major water level fluctuations during periods that would otherwise be naturally stable, such as mid-summer and winter. However, this type of dam regulation often conflicts with typical power generating regimes that are dictated by power demands (e.g., for heating in winter and air conditioning in summer) and therefore it is often not economically desirable (Hellsten *et al.*, 1996).

Other landscape level alterations and exploitation such as deforestation and intensive agriculture and irrigation can increase the demand on surface and ground-water reserves (Coops *et al.*, 2003). Large-scale natural disturbances such as forest fire, flooding, and drought can also have significant negative influences on aquatic systems and can affect the overall boreal landscape (Schindler, 1998). Anthropogenic influences may exacerbate natural disturbances thereby increasing the potential for local and landscape level impacts (Coops *et al.*, 2003; Danylchuk and Tonn, 2003; Hudon, 2004). For example, erosion due to heavily regulated water impoundments can lead to landslides, which can result in large-scale losses of wildlife habitat (Avakyan and Podol'skii, 2002). Careful, ecologically based water level regulation may act to reduce the effects of human and climate change on water bodies (Coops *et al.*, 2003).

EFFECTS OF WATER LEVEL FLUCTUATIONS ON BIOTA

Fishes

Due to their obvious dependence on water, fishes are among the most impacted organisms by fluctuating water levels. Water level fluctuations can alter fish behavior, distribution, and growth. Rogers and Bergersen (1995) noted a change in movement of largemouth bass (*Micropterus salmoides*) and northern pike (*Esox lucius*) in reservoirs between normal and drawdown conditions. Fischer and Öhl (2005) observed a distinct hierarchy in burbot (*Lota lota*) in respect to shelter occupation when such structures became scarce due to lowered water levels. Larger burbot out-competed smaller burbot for shelter until shelter became increasingly limited, at which point the larger burbot abandoned shelter altogether, and shelter was only occupied by the smaller conspecifics.

Flow regulation can influence the natural dispersion of larval and juvenile fishes through either increasing or limiting flow, which also affects their access to rearing areas (Bonetto *et al.*, 1989). Fishes in stable high-water systems frequently have better growth than those in stable low water or fluctuating systems. Slower growing species, such as brown trout (*Salmo trutta*), are particularly vulnerable (Flodmark *et al.*, 2004). Similarly, fish abundance in severely regulated systems is often lower than in the preregulated condition of the same system (Gaboury and Patalas, 1984).

Lake and river impoundments can be barriers to outflow, altering water discharge and water level for the purpose of creating or enhancing reservoirs. Bodaly and Lesack (1984) reported a sharp but short lived increase in northern pike abundance following the impoundment of a boreal lake in northern Manitoba. The first year class after impoundment was highly successful, likely because of increasing the area of flooded terrestrial vegetation used as spawning habitat. However, this large cohort was slower growing and in poorer condition when compared with the preimpoundment year classes. Subsequent year classes following impoundment were not as large, perhaps because the flooded vegetation defoliated over time and was less useable as spawning substrate. The impoundment did not affect adult pike abundance, or that of forage fishes. Lake whitefish (*Coregonus clupeaformis*) fishing grounds that were historically targeted were abandoned due to a redistribution of fish from these areas because of changes in water clarity and migration corridors. Lower quality stocks were then exploited in attempt to maintain catches. Catches were maintained post-impoundment only through increased fishing effort, but quickly declined with reduced effort (Rosenberg *et al.*, 1987). Fluctuating water levels in aquatic environments can lead to or exacerbate periodic conditions of low oxygen concentrations (hypoxia) or lack of oxygen (anoxia), which can seriously stress or kill fishes (Nickum, 1970; Davis, 1975; Casselman, 1978; Stefan *et al.*, 2001; Wetzel, 2001).

A recent study conducted by Cott *et al.* (2008), investigated the effects of winter water withdrawal on oxygen concentrations in small (<30 ha) Shield lakes in the Northwest Territories (NWT). Large volumes of water (10 and 20% of their respective under-ice volumes) were withdrawn from two lakes and compared with reference conditions. The oxygen concentration in both lakes was reduced by the withdrawal. The 10% withdrawal reduced oxygen slightly more than the colder and heavier snow load of the year prior. The oxygen concentrations in the 20% withdrawal lake declined well beyond that of climatic influences. The results indicate that winter water level fluctuations affect oxygen levels and are compounded by environmental factors. No effects were observed on temperature profiles or fish abundance as result of the withdrawals.

Oxygen Requirements of Fishes. On average, Canadian freshwater fishes require between 4 and 6 mg/l dissolved oxygen (DO), below which some may experience physiological stress (Davis, 1975). For

TABLE 1. Oxygen Concentration Thresholds for Select Fish Species Occurring in Northern Canada and Alaska (based on Doudoroff and Shumway, 1970).

Species	Age or Size	Lethal O_2 (mg/l)	Deaths	Exposure	Water (°C)	Methods/Thresholds
Broad whitefish: *Coregonus nasus*	1 day	1.9	–	Declining O_2	12	Cessation of opercular movements
	120 days	1.9	–	Declining O_2	12	Cessation of opercular movements
	209 days	1.1	–	Declining O_2	10	Cessation of opercular movements
Chum salmon: *Oncorhynchus keta*	Fingerling	2	–	–	–	Methods unknown
Yellow perch: *Perca flavescens*	78 g	<2.0	1	Declining O_2	19-24	CO_2 tensions 0-40 mmHg
	89-99 g	0.5-0.8	0.5	Declining O_2	12-21	Loss of equilibrium
	–	3.1	1	Constant O_2 48 h	15	Fish held in cage submerged in a lake in summer
	–	1.5	0.5	Constant O_2 48 h	4 or less	Fish held in cage submerged in a lake in winter
	7.6 cm	0.9-1.1	0.5	Declining O_2	18-27	Loss of equilibrium, graph interpolation
Burbot: *Lota lota*	830 g	<2.0	1	Declining O_2	12-18	CO_2 tensions 0-40 mmHg
	–	1.4-3.2	First	–	0	Methods unknown
Brook stickleback: *Culaea inconstans*	0.6 g	<2.0	1	Declining O_2	20-23	CO_2 tensions 0-40 mmHg
White sucker: *Catostomus commersonii*	265 g	<2.0	1	Declining O_2	17-18	CO_2 tensions 0-40 mmHg
Pearl dace: *Semotilus margarita*	5.3 cm	<2.0	1	Declining O_2	18-19	CO_2 tensions 0-40 mmHg
Inconnu: *Stenodus leucichthys*	–	4.0-4.5	First	–	0	Methods unknown
Northern pike: *Esox lucius*	–	3.1	100%	Constant O_2 24 h	15	Fish held in cage submerged in a lake in summer
	–	2.3	100%	Constant O_2 48 h	4 or less	Fish held in cage submerged in a lake in winter
	–	0.2-0.5	100%	Declining O_2	0-20	Methods unknown
	–	0.3-0.6	First	–	0	Methods unknown
	–	0.5-1.6	About 50%	Declining O_2	15-25	Water gradually replaced with low O_2 water
	1-2 year	0.7-1.4	–	–	15-29	Methods unknown

many cold and cool water fish species that live in northern Canada and Alaska, mortality can occur when oxygen concentrations become 2.0 mg/l or less (Doudoroff and Shumway, 1970) (Table 1). Fishes in lakes with long-lasting ice cover (six months or more) are more vulnerable to hypoxia than fishes in lakes with shorter periods of ice cover (Evans, 2005). Ice and snow cover eliminates wind influence on surface waters, and greatly reduces light penetration, in turn reducing photosynthetic activity (Magnuson and Karlen, 1970; Welch and Kalff, 1974; Barcia and Mathias, 1979; Stefan *et al.*, 2001; Wetzel, 2001). Any combination of circumstances where oxygen demands are greater than oxygen production will result in oxygen depletion (Nickum, 1970). Decreased primary productivity combined with increased respiration and bacterial oxygen demands reduce the available oxygen over the winter months. Stratification may exacerbate this effect in the hypolimnion of frozen lakes (Davis, 1975; Barcia and Mathias, 1979; Wetzel, 2001).

Oxygen concentrations are not usually distributed evenly in the water column of lakes and reservoirs, and often show depth-dependent profiles dictated by hydrodynamic processes such as mixing and stratification. In ice-covered water bodies, the highest oxygen concentrations typically occur directly under the ice, and often decline with depth and can be near zero in deep hypolimnetic waters due to water and sediment-associated biological oxygen demand (Casselman, 1978; Stefan *et al.*, 2001). Low oxygen concentrations often correlate with high free carbon dioxide concentrations, which may hinder respiration (Magnuson and Karlen, 1970). Reduced oxygen concentrations can lower the cellular metabolism in many fishes through the diminished capacity to transfer oxygen to cells as there is less oxygen transport across gill membranes (Randall, 1970).

In winter, some fish species respond to oxygen distribution changes by moving to the ice-water interface, which is usually more oxygenated (Casselman, 1978; Magnuson *et al.*, 1985). Fishes that are able to stay in this area are more apt to survive low oxygen conditions (Magnuson and Karlen, 1970). Lowered oxygen concentrations during ice-covered periods limits the available habitat for overwintering fishes compared with open water conditions (Casselman, 1978; Stefan *et al.*, 2001), a potentially stressful situation that is compounded by the thickening of ice, further reducing the overall under-ice water volume (Magnuson and Karlen, 1970). During times of severe oxygen depletion, Magnuson and Karlen (1970) noted that northern pike responded by staging at the ice-ceiling and moving very little. The northern pike melted slight "domes" in the ice ceiling from the action of water passing through their gills and presumably capitalized on slightly higher oxygen concentrations associated with these domes. Occasionally, the northern pike would swim into anoxic water for short periods, perhaps searching for conditions that were more favorable. These behaviors seemed to be beneficial, as the northern pike persisted longer than bluegill (*Lepomis macrochirus*) and yellow perch (*Perca flavescens*), which were more active (Magnuson and Karlen, 1970).

Fluctuations in water levels and inflows can also impact the availability of oxygen to fishes. For example, a year of low precipitation can reduce or eliminate the amount of oxygenated water that an inlet stream may provide to a given water body (Danylchuk and Tonn, 2003). Such circumstances are particularly influential during periods of ice-cover when oxygen may not be replenished until snow and ice begin to melt and recharge water bodies. In midwinter, recharge can occur to some degree if mild weather induces a partial melt (Magnuson and Karlen, 1970), but in northern regions full oxygen recharge does not normally occur until spring melt. Therefore, winter is a tenuous period for fish survival, particularly for fish living in cool or cold water environments with long periods of ice-cover (Stefan *et al.*, 2001).

An adequate supply of oxygen is required for fishes to meet metabolic requirements and to fulfill regular daily activities. The metabolic energy available to a fish to perform routine life processes above a resting state – such as feeding, predator avoidance, migration, or spawning – is known as "scope-of-activity" (from Evans, 2007). As ambient DO is reduced, scope-of-activity levels and growth decline (Evans, 2005). Cold-water species such as lake trout (*Salvelinus namaycush*) are particularly vulnerable to hypoxia when oxygen drops below critical concentrations in the hypolimnion. In an effort to minimize predation by older, larger lake trout, juvenile lake trout have been observed living in the suboptimal conditions of the hypolimnion to remain spatially separated from adults. Because of staying in oxygen poor waters, these juvenile fish often grow slowly and may retain their parr marks for several years (Evans, 2005). A decline in oxygen of only 1 mg/l below optimal levels (7 mg/l) can have significant effects on lake trout metabolism, growth and recruitment (Evans, 2007). Davis (1975) suggests that the optimal or preferred habitat for salmonids is 6 mg/l. This represents an average for the family. Complete die-off of lake trout and other species in the salmonid family can occur when oxygen concentrations dip below 3 mg/l (Evans, 2005).

Compounding factors such as drawdown or nutrient enrichment can decrease the oxygen present in the hypolimnion during summer or winter. Evans (2007) recommends a DO criterion of 7 mg/l be used for the protection of lake trout based on the rationale that oxygen concentrations below this level will hinder the fishes' scope-of-activity requirements.

Winterkill. If oxygen concentrations are low enough, fishes may not survive the winter. This condition is commonly referred to as "winterkill" (Greenbank, 1945) and can have serious implications for fish populations (Barcia and Mathias, 1979). Winterkill can be a natural phenomenon occurring when oxygen inputs are reduced or eliminated by ice cover and the remaining oxygen is used through biological activity. In an inventory of South Dakota lakes with a high probability of winterkill, Nickum (1970) found that most are shallow (<5 m in maximum depth) and are eutrophic or have highly organic bottoms. Not all shallow lakes are prone to winterkill and it is unlikely that deeper lakes would experience winterkill (Nickum, 1970). Lakes that have predominately gravel substrates are normally well oxygenated compared with those with organic substrates, likely due to lower decomposition rates (M. Lilly, GW Scientific, Fairbanks, Alaska, unpublished data). Similarly, lakes that have clear ice and are blown clear of snow are unlikely to experience winterkill as light penetration can allow photosynthesis to occur. Lakes prone to winterkill often have up to 50% of their volume consumed as ice and generally do not have an inflow or outflow, or the inflow or outflow freezes in the winter. Light penetration was the single most important factor dictating the winterkill of lakes investigated by Nickum (1970).

Winterkill can have a strong influence on long-term ecosystem dynamics within affected water bodies. Conditions that lead to winterkill can affect fish population recruitment and depress population densities, particularly for large bodied fish such as northern pike (Pierce and Tomcko, 2005). In oxygen-deprived water bodies, oxygen is often only present in a very thin layer directly under the ice surface and small fishes may be able to make use of this resource more effectively or acclimate more easily than large-bodied fish (Casselman and Harvey, 1975; Hall and Ehlinger, 1989; Danylchuk and Tonn, 2003). In most cases, young fish or fishes that have a small adult size are more resilient to low oxygen concentrations than adult large-bodied fishes (Casselman and Harvey, 1975). Less active fish have a higher threshold of low oxygen tolerance than that of active fish, generally eat less, are usually slow growing and require less oxygen to perform regular life processes than active faster growing fishes (Casselman and Harvey, 1975). If winterkill eliminates large fishes, including top predators, but not small fishes, the top-down regulation of that ecosystem can be disrupted. Such a disruption can result in a cascading change in the trophic dynamic balance of the system (Paine, 1963; Terborgh *et al.*, 2001).

Fishes are not the only animals that can be impacted by winterkill. Overwintering amphibian larvae and invertebrates also require oxygen concentration of appropriate levels to sustain themselves. Smith *et al.* (2005b) noted an absence of bullfrog (*Rana catesbeiana*), and green frog (*Rana clamitans*) tadpoles in the year immediately following a winterkill of a small pond. This suggests that over-wintering tadpoles succumbed to winterkill conditions and there was breeding failure the year immediately following the winterkill. Hemipterans, coleopteran larvae, and bluegill sunfish (*L. macrochirus*) were also impacted, but like the anuran tadpoles did show trends of recovery in subsequent years (Smith *et al.*, 2005b).

Winter drawdown of reservoirs can induce winterkill if oxygenated water is removed, through drawing or flushing the oxygenated surface waters within a reservoir, leaving only poorly oxygenated water (Gaboury and Patalas, 1984; Järvalt and Pihu, 2002). Drawdowns can also affect fish and other components of the aquatic ecosystem through partial or complete reduction of littoral habitat. In an experiment conducted in Lake 226 at the Experimental Lakes Area in northwestern Ontario, the effects of a hydroelectric drawdown in a boreal environment were simulated with volumes of approximately 30 and 45% removed from a small lake (16.1 ha) over two successive winters (Jansen, 2000; Mills *et al.*, 2002; Turner *et al.*, 2005). These drawdowns caused a significant reduction in recruitment of lake whitefish (*C. clupeaformis*) in years 1, 2, and 3 following the initial drawdown. Whitefish spawning shoals with incubating eggs were exposed by lowered water levels causing the eggs to desiccate or freeze (Jansen, 2000; Mills *et al.*, 2002). This supports the conclusions of Gaboury and Patalas (1984) who observed similar impacts on lake whitefish and cisco (*Coregonus artedi*) associated with a hydroelectric drawdown at Cross Lake in Manitoba.

Water Level Fluctuation to Manage Fisheries. Fisheries managers often focus their efforts to mitigate impacts of drawdown through the moderation and timing of flows. However, water fluctuations are also used as a fisheries management tool for enhancement of existing populations or control of invasive species. Using water level fluctuations can be more cost efficient for controlling species than chemical controls (Lantz *et al.*, 1967). Water drawdown has also been used as a method for aquatic plant control (Tarver, 1980), often in association with fisheries management objectives (Lantz *et al.*, 1967; Heman *et al.*, 1969). Dense plant growth can inhibit the hunting success of highly prized piscivores such as largemouth bass (*M. salmoides*) and northern pike. Dense vegetation also makes angling difficult, while thinning vegetation can increase sport-fishing opportunities (Lantz *et al.*, 1967; Olson *et al.*, 1998). Often vegetation control in regulated water bodies entails drawing down water levels to a point where aquatic vegetation is left to dry or freeze or is harvested using dedicated plant-harvesting equipment (Olson *et al.*, 1998). Planned drawdowns can have the effect of increasing game fish while reducing nongame fish species and dense aquatic plants. Lantz *et al.* (1967) observed an increase in sport fishing harvest of over 250% following a water fluctuation program that reduced noxious vegetation cover by 95%. With plants exposed, forage fish are forced into the open and are more readily preyed upon by game fish. This translated into higher yields of desirable species, at least in the short term (Lantz *et al.*, 1967; Heman *et al.*, 1969).

Increasing water levels or reducing drawdowns during certain times of the year can also affect fish populations in controlled systems. Groen and Schroeder (1978) and Järvalt and Pihu (2002) reported an increase in spawning of northern pike and walleye (*Sander vitreus*) following an increase of spring water levels that flooded terrestrial vegetation and rocky shorelines, which are the preferred spawning habitat, respectively, for these species. In addition, by reducing the spring drawdown, walleye that aggregate around dam outflows during spawning are less likely to be flushed out of the system (Groen and Schroeder, 1978).

Winter drawdown has also been used to instigate winterkill conditions to control invasive species such as common carp (*Cyprinus carpio*) (Verrill and Berry, 1995). Summer drawdown has been used to break thermal stratification allowing for an overall warmer system and therefore increased feeding and growth of warm-water game fish such as largemouth bass (Heman *et al.*, 1969). However, if water temperatures become too high for the target species, growth can be reduced (Casselman, 1978).

Fluctuation in water levels may change the structure of both fish and aquatic plant communities (Lantz *et al.*, 1967; Tarver, 1980). As a result, successful control of plants and/or animals using drawdown is variable because target species may not be impacted and desired species may be reduced (Tarver, 1980). Fisheries manager can time drawdowns considering the biology of the fish species present in the lake or reservoir in question to ensure that target species are not adversely affected. For example, many fish species are critically dependent on shallow littoral areas for spawning, rearing, and feeding during their early development period, and therefore any fluctuation during this period could have detrimental effects on year-class recruitment (Groen and Schroeder, 1978). Different fish species use the zone of fluctuation at differing times of year, and therefore the spawning and rearing habits of fish species should be considered when developing a water level fluctuation schedule. Of particular importance is ensuring adequate springtime water levels and maintaining stable and adequate levels during mid-summer and winter periods when fishes are particularly sensitive to perturbations in water level (Lantz *et al.*, 1967; Groen and Schroeder, 1978; Rogers and Bergersen, 1995).

Furbearers and Waterfowl

Water fluctuations and drawdowns can have implications for waterfowl and fur bearing mammals. Muskrats make denning houses in shallow water bodies using mud and aquatic vegetation. Dannel (1978) found that the vast majority of muskrat lodges were within 1 m of water depth, and the mean water depth at lodge sites was 0.2 m. Relatively constant water levels are required to enable muskrats to access food and construction materials during periods of ice-cover (Glass, 1952). Winter water level reductions can prevent semi-aquatic animals such as muskrats from accessing their burrows (Avakyan and Podol'skii, 2002). In winter, muskrats feed on plant material under the ice (Allen and Hoffman, 1984); changes to water level regimes that influence the amount of plant material in feeding areas and low water may lead to freezing of food resources that would otherwise be available. If water levels are too low, muskrats are forced to find new feeding areas, increasing their vulnerability to predation and hypothermia. Drought or other low water events can concentrate muskrats, leading to higher rates of social conflict, predation, and disease (Perry, 1982). Further, when muskrats are forced to search for food during winter, they run an increased risk of being frozen out of their dens (Perry, 1982). Water level fluctuation and control is the primary method of muskrat population management as it is the most influential variable determining muskrat abundance, even more so than the type of vegetation present. Reduced water levels can prevent the establishment of plants such as cattails (*Typha* sp.) that muskrats use for food and building materials. Parasite loading and disease also increase with suboptimal water levels (Perry, 1982).

In a study of muskrat lodge use during the winter, Messier *et al.* (1990) found that shallow-water conditions of a regulated system were less conducive to muskrat over-wintering in comparison to normal water levels, regardless of the habitat type. The reason for the lower muskrat lodge inhabitation during winters with low water levels is not fully understood. Muskrats need adequate year-round water levels around their dwellings to feed and avoid predation (Messier *et al.*, 1990).

A reduction of spring floodwater induced by water regulation of the Peace River system, Alberta, has had disastrous effects on muskrat populations in Wood Buffalo National Park. The dam decreased the delta marsh area by 40%, shrinking lakes and edge habitat, and allowing many lakes to freeze to the bottom. Prior to dam construction (1965-1966), there were an estimated 144,000 muskrats in the delta marsh, while there were fewer than 2,000 muskrats in 1971-1972 after the construction of the Bennett dam (Avakyan and Podol'skii, 2002).

Beaver (*Castor canadensis*) require a permanent water-source in which to live, and prefer water bodies that are seasonally stable. Water provides cover from predators, enabling them to feed and reproduce in relative safety (Allen, 1983). Unlike other animals (besides humans), beavers have the ability to control the water levels in their environment through the construction of dams. Beavers are generally absent from water bodies where they cannot control water levels (Slough and Sadleir, 1977). Water bodies that have highly variable seasonal or annual water level fluctuations are not suitable beaver habitat (Allen, 1983). If water levels decrease, particularly in winter, their lodge entrance may be blocked or be above the ice surface. In a study of water drawdown effects on beaver in northern Minnesota, Smith and Peterson (1991) found that beaver in fluctuating water systems spent more time outside of their lodges during ice-covered periods than beaver in stable systems. Although winter drawdown itself did not account for observed beaver mortality, a higher instance of mortality (through starvation and predation) occurred than when compared with water bodies that were not drawn down. Also, kits that overwintered in stable water systems were twice as heavy as those from the water body where winter drawdown occurred. Beaver normally live in water bodies that are deeper than those occupied by muskrat, and with their ability to adjust water levels to suit their needs. Beaver are more adaptable and resilient to water withdrawals from ice-covered water bodies than muskrats. However, if water levels decrease significantly during the winter, entrances to lodges can become closed by ice and beaver may become trapped in their lodges or forced to desert their lodges and/or food caches. These factors would greatly increase the risk of mortality from exposure or predation. During the winter, inlets and outlets of many water bodies are frozen, and if substantial winter withdrawal occurs, beaver may not be able to regulate the water levels to suit their habitat requirements. Smith and Peterson (1991) suggest that to protect beaver, winter water drawdown >0.5 m should not be conducted in water bodies containing beaver.

Water level fluctuations, both short term and long term, have a direct influence on the food availability, foraging opportunities, and nesting habitat for Mallards (*Anas platyrhynchos*) and other dabbling ducks (Allen, 1987). For example, Mallards prefer to forage around the waters' edge in depths of 20-40 cm where both terrestrial and aquatic macro-invertebrates occur, as well as the mast crop from aquatic, emergent, and terrestrial vegetation (Heitmeyer, 1985). Water level fluctuations can have negative impacts on littoral plant and invertebrate abundance (Turner *et al.*, 2005), which in turn can have negative impacts on dabbling duck habitat. Dabbling ducks often nest in riparian areas around water bodies and lowered or raised water levels can disrupt these habitats or the proximity of these habitats to feeding areas. Reduced nesting and molting habitats have resulted in lower duck production (Rosenberg *et al.*, 1987).

The yellow-billed Loon (*Gavia adamsii*) occurs throughout northwestern Canada and Alaska and is a sensitive species whose breeding grounds are being threatened by resource development. The yellow-billed Loon has a restricted range, low abundance, and very specific habitat requirements. Its reproductive success is strongly influenced by environmental perturbations. These birds nest exclusively along lake shorelines, and therefore depend on consistent water levels. Reproductive success of yellow-billed loons is largely dependent on the timing of the spring ice melt. Early or late ice melt will alter the shoreline at the time of nesting, which can make a water body unsuitable for nesting (Earnst, 2004). Ice roads built over breeding lakes can delay ice melt needed for suitable nesting habitat, resulting in delayed hatches, which decreases rearing time and results in poorer brood-rearing success. Delayed recharge can result in lower than average water levels during nesting, which can strand nesting sites and reduce the probability of successful breeding (Earnst, 2004).

For centuries, northern residents have relied on the land as an integral part of their cultural and subsistence way of life, and therefore they have a vested interest in the development of northern environments. Impacts to furbearers and waterfowl can hinder the subsistence lifestyle and decrease the cultural value of these lands to aboriginal people and fur harvesters (Townsend, 1975).

Littoral Biota

Fluctuating water levels can affect aquatic and riparian plant communities both positively and negatively. Periodic flooding is important for retaining and replenishing nutrients and other materials that contribute to the development of plant communities and local ecosystem processes (Pinay *et al.*, 1990). Persistently elevated water levels can lead to defoliation of littoral vegetation, eventually causing a shift in the type of vegetation present (Hudon, 2004) and induce a cascade of effects on organisms dependent on the previous plant community (Townsend, 1975; McGowan *et al.*, 2005). Shifts in plant communities may also reduce overhead cover (Bodaly and Lesack, 1984) or eliminate spawning grounds previously available to fishes. Depending on the season, reduced water levels can stress littoral environments by desiccating or freezing littoral sediments and vegetation (Lantz *et al.*, 1967; Heman *et al.*, 1969; Tarver, 1980; Coops *et al.*, 2003). Lower winter water levels can cause ice scouring within the littoral zone, which further compounds the stress of dry and freezing conditions (Coops *et al.*, 2003). Certain species are better suited to endure such harsh conditions, which often results in a shift in the littoral vegetation community where hardier species often become the new dominant vegetation (Hudon, 1997, 2004; McGowan *et al.*, 2005; Furey *et al.*, 2006). Shifts in the plant community can impact organisms that were dependent on the plant community (Hudon, 2004).

In the Lake 226 experiment, Turner *et al.* (2005) monitored the aquatic plant community and found that littoral plants, including algae, were significantly affected by drawdown. The biomass of benthic algae was reduced due to loss of habitat suitable for colonization (e.g., rock and woody debris surfaces). Macrophytes initially decreased in percentage cover by up to two-thirds. Post-drawdown recovery was variable among species. Of the species monitored, *Carex* spp. became almost completely absent, *Myriophyllum* spp. were relatively unaffected, and pondweed (*Potamogeton* spp.) increased in biomass and frequency. This effect on plant communities was attributed to loss of wetted habitat through a reduction in water level (Turner *et al.*, 2005). McGowan *et al.* (2005) made similar observations on plankton and macrophyte communities exposed to winter drought-like conditions in prairie lakes. There were few detectible effects on the food web structure of phytoplankton or zooplankton following a 50% reduction in lake level. However, there was a shift in macrophyte composition, from a community dominated by *Ceratophyllum demersum* to one of *Potamogeton pectinatus*, and a 2.5-fold increase in macrophyte abundance. Hudon

(2004) also noted an increase in *Potamogeton* spp. biomass following lower than normal water levels in the St. Lawrence River.

Aquatic invertebrates make up a substantial portion of faunal life in northern aquatic ecosystems, yet few studies have investigated the response of benthic and limnetic invertebrates to water withdrawal and fluctuating water environments. Areas of benthic habitat within regulated lakes can have >6,000 m^2 (Rothwell, 1951, *in* Hunt and Jones, 1972).

Water level variations outside of normal seasonal conditions can have significant impacts on the survival of aquatic invertebrates. Aquatic invertebrates often depend on specific types of vegetation for food, shelter and egg deposition, and any shift within the macrovegetation community can cause a drastic reduction of the invertebrate population (Hunt and Jones, 1972). Often lakes that experience unusual water level fluctuations initially experience a partial or complete reduction in invertebrate species, which may take several years to recover and then often with a different species assemblage (Hunt and Jones, 1972; Smith *et al.*, 2005b). This initial invertebrate reduction and reorganization reduces food sources for many fishes and promotes a shift in the dominant aquatic invertebrate species (Hunt and Jones, 1972). Rigler (1985) found no evidence that benthic invertebrates residing in the littoral areas of an Arctic lake tried to avoid freezing by moving to deeper parts of the lake that did not freeze, with the possible exception of chironomids.

Aquatic insects often comprise the majority of macroinvertebrate biomass within freshwater water bodies, many of which require emergent vegetation to complete their metamorphosis from larva to adult (Thorp and Covich, 1991). During metamorphosis, many Orders of aquatic insects, including mayflies, dragonflies, and damselflies, climb or fly to emergent vegetation to shed their larval casings and emerge as adults (Thorp and Covich, 1991). If water levels are higher than normal, emergent macrophytes can become flooded, reducing available substrate and therefore opportunities for many macroinvertebrates to emerge and complete their life cycle.

Jansen (2000) showed the impact of winter drawdown in lakes on aquatic invertebrates in the aforementioned Lake 226 study. Zoobenthos were significantly impacted, and losses were most severe in areas that froze or dried out. During the winter season, many invertebrates rely on specific littoral substrates as overwintering habitat. Winter drawdown can expose littoral substrates to temperatures below 0°C, or lead to ground-fast ice, consequently freezing the substrate and the associated invertebrate community. This freezing may cause shifts in benthic invertebrate community structure as a result of species specific tolerance levels to freezing and temperature regimes. When comparing long-term trends in benthic macroinvertebrates between seasonally regulated reservoir and a natural lake, Furey *et al.* (2006) noted that biomass and densities were greater in the regulated reservoir and that the effects of drawdown on benthic macroinvertebrates extended below the drawdown exposure zone. Species that were resistant to desiccation, Chironomids in particular, flourished in the littoral areas of the regulated reservoir. Also, the regulated reservoir resulted in an expanded epilimnion, which facilitated the distribution of littoral benthos further from shore than those in the natural lake.

Phytoplankton and zooplankton are resilient to water level fluctuations. In the Lake 226 study, phytoplankton and zooplankton abundance was reduced, but only small changes in the relative abundance and species diversity occurred for cyanobacteria and cryptophytes. However, plankton densities per unit volume stayed consistent, so the reduction in total abundance was related simply to the overall reduced lake volume during drawdown. Water chemistry, rate of photosynthesis from phytoplankton, and nutrients were relatively unchanged (Turner *et al.*, 2005).

Also, plankton populations may be indirectly affected by fluctuating water levels. For example, Hall and Ehlinger (1989) found that plankton communities changed after a winterkill of large fish lead to increased plankton predation from growing abundances of small fish species that were tolerant of the low oxygen conditions. McGowan *et al.* (2005) noted an increase in zooplankton population following fish winterkill, due to the overall reduction in zooplankton predation from fish. Nickum (1970) found that in lakes prone to winterkill, phytoplankton populations less diverse and often dominated by blue-green algae, particularly *Aphanizomenon* sp.

WATER WITHDRAWAL IN NORTHERN REGIONS

Northern regions of North America, such as the NWT and northern Alaska are increasingly being developed, primarily for the extraction of natural resources. For example, the NWT has one of the fastest growing economies in Canada with an economic growth rate of 79% from 1999 to 2004, compared with the national average of 16% for the same timeframe (Statistics Canada, 2008), with the oil and gas exploration and diamond mining being the most active industry sectors (Cott *et al.*, 2003; Birtwell *et al.*, 2005). Large-scale projects, such as the Mackenzie Gas Project (a proposed pipeline to bring Arctic gas to southern markets) require large volumes of freshwater for construction, development, and operational activities (IORVL, 2004). The North Slope of Alaska has had continued development of new oil and gas fields for more than 20 years. Current exploration and land-leasing is leading to the development of new fields, such as the Alpine field in the Colville River coastal area. With the pending development of new oil fields and the potential future construction of an Alaskan gas line, there will be an increased need for water resources.

In the Canadian north and Alaska, many industrial activities require water, such as the construction of winter roads, ice drilling pads, ice landing strips, drilling, and camp use. This water is most often drawn from ice-covered lakes (Adam, 1978; Baker, 2002; IORVL, 2004; Cott *et al.*, 2005; Miller, 2005). Additionally, northern communities rely on seasonal winter roads to transport supplies and to access regional centers (Government of the Northwest Territories, Department of Transportation and Transport Canada, 2003; Hinzman *et al.*, 2005). Over 40% of the NWT highway infrastructure is comprised of winter roads (Government of the Northwest Territories Department of Transportation, 2007). Winter roads are typically constructed in December, once the terrain is adequately frozen, and maintained until April. Because of their seasonal nature and construction materials, winter roads are generally considered to have reduced environmental consequences for terrestrial ecosystems compared with permanent road construction (Hinzman and Lilly, 2004) if they are decommissioned properly with stream-crossings removed allowing for natural melting and water flow (Adam, 1978). Winter roads, however, require a substantial amount of water for their construction, and can lower water levels reducing the overall lake volume. Nolan (2005) reports that approximately 3.5 $(\pm1.2) \times 10^6$ l (3,500 m^3) of water is required to construct 1 km of winter road over tundra. Because of this large water requirement, the impact of water withdrawal for winter road construction on over-wintering fish has been identified as a concern for many years (Berger, 1977; Adam, 1978).

Remote locations and high transport costs dictate that water should be withdrawn from the closest possible source. Because of the high volume of water required and the high transportation costs associated with moving water, selecting routes that have frequent water-sources is necessary. Winter road construction becomes financially unfeasible if the distance between water-sources is greater than 8 km (Adam, 1978). Often the only available water-sources are small lakes (<50 ha) with limited or no recharge capabilities (Cott *et al.*, 2005). Typically, water is withdrawn from such lakes using water trucks with the intake set just below the ice surface, which often corresponds to the region of highest oxygen concentration in the lake. Water withdrawal from this oxygenated layer can reduce the overall winter oxygen mass in the lake (Cott *et al.*, 2008). Many of these lakes are small and have limited water volumes prior to water extraction; this is further reduced as ice thickens. These small water bodies normally do not have water inputs during the winter months to renew oxygen reserves. Natural factors, such as prolonged ice-covered periods, can reduce oxygen concentrations in a water body and when combined with the effect of winter water withdrawals, can alter the oxygen balance and can lead to winterkill (Cott *et al.*, 2008). Effects may differ depending on climate, land use, lake characteristics, species present (Rogers and Bergersen, 1995; Turner *et al.*, 2005), and natural disturbance regimes (Danylchuk and Tonn, 2003).

Fishes are also particularly vulnerable to winter water withdrawal from streams. Flow is generally low during the winter and withdrawals not only reduce available water downstream, but the reduced flow encourages additional ice formation, which further reduces habitat and oxygen production (Cunjak, 1996).

Winter Roads

Although there are many industrial demands for water during the winter, such as drilling and camp use, water for the purpose of winter road construction is the most common. A winter road is a road that is built of snow, ice, or a mixture thereof that remains functional only during the winter season. The route can be annual (one season) or perennial (used repeatedly over several winters). Due to their nature, winter roads generally have less environmental impact than permanent roads (Hinzman and Lilly, 2004). For instance, winter roads melt each spring without leaving a persistent footprint, often do not require extensive land clearing to construct (especially in tundra areas), and seasonally restrict access to potentially sensitive wilderness areas (Adam, 1978).

Winter roads can be separated into three broad categories: (1) winter trails, (2) snow roads, and (3) ice roads.

Winter Trails. Winter trails are used where load and volume of traffic are low, or are restricted to the use of high floatation vehicles only (vehicles that distribute their weight efficiently through the use of wide tracks or balloon tires). If clearing of vegetation is not required, such trails can often be made with a single pass of a vehicle. Seismic lines are an example of simple winter trails. These are the least developed of the three winter road types, and require relatively little water to construct (Adam, 1978).

Snow Roads. Snow roads are made with compacted snow as a base to accommodate intermediate volumes of traffic and load weights. Snow is compacted with graders, rollers, or drags (such as lumber or heavy tires dragged behind vehicles), and usually require some amount of snow fill in low areas or grading of high spots (Adam, 1978). Water is also required to consolidate snow infilling of depressions along snow roads. Snow roads can be built by compacting the existing snow pack or can be fabricated by compacting artificial snow. Artificial snow is sometimes required in regions or years of low precipitation and is made with industrial snow making equipment similar to those used on ski hills. Large volumes of water are required to make artificial snow (Adam, 1978). Snow roads are sprayed with water to form an ice cap of approximately 2.5 cm if a more durable road surface is required. Approximately 300,000 liters of water is required to make 1.6 km of ice-capped snow road, if a natural snow base is present (Adam, 1978).

Ice Roads. Ice roads are made of ice either by thickening the existing ice on lakes and rivers or by spreading water over a land-based roadway making a smooth surface of a sufficient thickness to support the traffic anticipated. Ice roads on lakes and rivers are the most common type of ice road (Adam, 1978). They are normally made by removing the insulating blanket of snow from the ice surface in a swath much wider than the road allowing for advance thickening of the ice. Ice profiling is conducted to ensure that the required thickness is achieved, and if required, spraying or flooding is carried out to increase ice thickness (Adam, 1978). In some areas, ice is harvested from ground-fast areas of lakes using special ice-chipping equipment. These ice chips are applied to the road surface as an aggregate. Water is then sprayed over the aggregate filling in the interstitial spaces and forming a thicker road surface more quickly than watering snow or frozen soil (Adam, 1978). Ice roads can accommodate the largest loads and traffic volumes and are the road type favored as perennial supply roads to northern communities or major industrial developments such as Canada's diamond mines. Ice roads have the greatest water requirements of the three winter road types, from 1,300,000 to 3,500,000 l/km (Adam, 1978; Nolan, 2005). On perennial roads water withdrawal from the same water bodies year after year is common (Adam, 1978).

Some winter roads may be a composite of the above-mentioned types. For example, a snow road may cross rivers making it necessary to make ice bridges on winter roads, or an ice road may have spur roads leading from them that have a lower traffic or load requirement so snow roads or trails may be all that is required.

REGULATING WATER WITHDRAWAL IN THE NWT

In the NWT, water use is regulated through the issuance of water licenses. The administration of the water license application review and issuance is conducted by various land and water boards, depending on the region in which the water is to be drawn. Generally for oil and gas exploration, water use of $<100\ m^3$/day does not require a water license and water use of between ≥ 100 and $\leq 300\ m^3$/day requires a Type B water license. For all other industrial activities water usages of $\geq 300\ m^3$/day requires a Type A water license. Type A and B water licenses differ in the amount of review, public consultation and level of sign-off required, with the requirements for a Type A being more rigorous (Erlandson & Associates, 2000, 2001, 2002a,b).

Water licenses allow for water withdrawal on a volume per day basis, rather than an overall limit, a limit based on the volume of the water body, the number of users per water body, or the biota present in a water body. Although these factors may be considered during the review of the application, there exists a potential risk to overwintering fish and fish eggs with water withdrawal limits set in this manner alone. In Canada, the killing of fish by means other than fishing (e.g., through water withdrawal induced winterkill) is prohibited under Section 32 of the federal *Fisheries Act* (Government of Canada, 1985). Keeping below withdrawal thresholds that will negatively impact fishes will minimize the risk of violating the *Fisheries Act* from winter water withdrawal activities.

Imposing thresholds for winter water withdrawal to protect fish have been proposed in the past. For instance, the Berger Inquiry of the 1970s was set up to determine if the NWT was ready from a social, political, and environmental protection standpoint, to have its Arctic gas fields developed. This inquiry recommended that no water should be withdrawn from lakes shallower than 3.7 m in maximum depth as they are potentially sensitive over-wintering fish habitat, and that no more than 10% of the under-ice volume of lakes greater than 3.7 m in maximum depth should be drawn (Berger, 1977). These recommendations were never implemented in the NWT.

With an increasing demand for winter water-sources and a mandate to protect fisheries resources, the federal Department of Fisheries and Oceans (DFO), in conjunction with industry and other regulators, developed the *DFO Protocol for Winter Water Withdrawal in the NFT* (DFO, 2005) (hereafter "the DFO protocol"). The DFO protocol contains the limits to water withdrawal as a percentage of available under-ice water volume (assuming maximum ice thickness), and takes into consideration the latitude and maximum water depth of a lake. The threshold currently used is 5% of the available under-ice water volume for lakes with a maximum depth of at least 1.5 m or greater than the predicted maximum ice thickness (this is being revised to 10% as per recent study findings (Cott *et al.*, 2008)). The maximum ice thickness values are given for three different regions of the NWT to account for geographic variability in ice thickness. A 0% threshold is recommended for lakes with a maximum depth <1.5 m plus the maximum predicted ice thickness, as any fish living in these shallow lakes could be particularly vulnerable to water level and oxygen perturbations. If the maximum depth of the water body is less than the predicted maximum ice thickness, a threshold of up to 100% can be used as the water body would not be viable over-wintering fish habitat. The DFO protocol also outlines methodologies for conducting water volume estimations through bathymetric surveys (Cott *et al.*, 2005). Due to the limited information available at the time of its inception, the protocol was intentionally designed to be conservative, utilizing a precautionary approach (DFO, 2002).

REGULATING WATER WITHDRAWAL IN ALASKA

In Alaska, water withdrawals from fish bearing waters are regulated by the Alaska Department of Natural Resources (ADNR), Office of Habitat Management and Permitting (OHMP), and Division of Mining Land and Water (DMLW), Water Resources section. There are two permitting processes for lakes considered as potential over-wintering fish habitat. One type of permit, issued by DMLW, is a temporary water use permit (or water right in some cases) that allows a specific volume use over an annual (January to December) time period (these have also started to be issued/tracked based on the water year in some cases on the North Slope). The second type is a Fish Habitat Permit, which is based on a shortened annual water cycle from approximately October to June. Recently, Hinzman *et al.* (2005) suggested the use of a standard water year for permitting purposes, as this better corresponds to the natural hydrologic cycle for North Slope lakes. The current practice in Alaska is (1) for lakes with overwintering but nonsensitive fish species [i.e., ninespine stickleback (*Pungitius pungitius*) and Alaska blackfish (*Dallia pectoralis*)], 30% of the under-ice volume can be used after incorporating an assumed ice thickness of 5 feet, (2) for lakes with any fish species other or additional to ninespine stickleback or Alaska blackfish) only 15% of the under-ice volume can be used, using an assumed ice thickness of 7 feet, (3) for lakes that are documented habitat for especially sensitive cold water species (such as lake trout) ADNR discourages the use as a water source, and (4) ADNR OHMP does not actively regulate for lakes that are not fish bearing. If the species composition in a lake is not known, ADNR does not regulate water use but recommends that use be conducted as if sensitive fish species are present. ADNR, Division of mining, Land and Water also regulates water use by means of issuing water rights and/or temporary water use permits using similar criteria as mentioned above, however will typically only permit a maximum of 20% of the total lake volume for lakes without fish volume regardless of the species assemblage (William Morris, Habitat Biologist, ADNR, February 2004, personal communication,). For most lakes, the maximum volumes of water are not generally taken as the ice road construction methods result in volumes being limited by transport distances. Usually lake densities are high enough that there is less of a logistical need to use all the permitted volume. This will change for future developments in areas where there are few lakes or the lakes present are small and shallow.

FUTURE RESEARCH

More research is required to test and refine mitigation and best management practices to have confidence that they are effective in minimizing or avoiding environmental impacts. Potential for impacts on oxygen concentrations are a key factor in determining the suitability of a lake as a water-source. Individual fish species react differently to oxygen concentrations and different temperatures. Species-specific research on the sublethal effects of decreased oxygen levels on fishes is required in order to determine oxygen thresholds of individual fish-bearing lakes. Further, different lake characteristics, such as basin shape, may account for some of the oxygen concentrations and temperature differences between the lakes, but this study did not include the wide range of lake types that occur in areas where winter withdrawals occur (e.g., small Shield lakes versus tundra ponds). Differences in specific lake characteristics, such as basin shape, substrate, oxygen concentrations, and species composition, can change the impacts of winter water withdrawal. Our current understanding of lake response to winter water level fluctuations should be widened with additional studies that evaluate a broader range of lake types and the influence of substrate and vegetative composition and water chemistry. Further understanding of the influence of increasing climatic variability on northern lakes will allow for more reliable predictions of future lake conditions, and will be useful in assessing the impacts of climate change and increased development. As some water-sources are used year after year, more information is required on the effects of repeated annual (perennial) withdrawals to determine if fishes adapt or suffer under such conditions or there are cumulative impacts if this occurs. Alternatives to using lakes as water-sources are being investigated on the Alaskan North Slope. Pits left over from gravel quarries made during the development of the North Slope oil fields were connected through channels to nearby rivers and allowed to fill. These previously abandoned gravel pits are now being used as water-sources, and are serving as over-wintering habitat for fishes, a habitat type lacking in the area. (William Morris, Habitat Biologist, Alaska Department of Natural Resources, February 2003, personal communication). Creative ideas, such as filling gravel pits with water to use as water sources, may help reduce dependency on small lakes and tundra ponds, and enhance fish habitat.

SUMMARY

As industrial requirements for water in northern regions continue to grow, pressure to extract and sell Canadian water to other countries will increase, and demands for transporting northern water over long distances to support agricultural activities in water-stressed southern regions will become increasingly attractive. It is for these reasons that the need for focused attention on the effects of water withdrawal on aquatic systems is becoming increasingly important. While the effects of water level manipulations on aquatic biota are often acknowledged, quantifying impacts remains largely unexplored (Paller, 1997).

Water level fluctuations, through dams and water withdrawals, have a profound influence on landscapes in boreal regions and throughout the world. Aquatic ecosystems are particularly vulnerable to water level perturbations (Townsend, 1975; Gaboury and Patalas, 1984; Järvalt and Pihu, 2002). For fishes in northern ecosystems, winter is a particularly sensitive time of year due to the potential for reduced oxygen stores and the risk of winterkill (Barcia and Mathias, 1979; Stefan *et al.*, 2001). Water withdrawals during winter increase the risk to fish, benthos and vegetation through reduction of littoral habitats (Jansen, 2000; Turner *et al.*, 2005), and the potential for winterkill through the reduction of available oxygen (Mills *et al.*, 2002; Cott *et al.*, 2008). Due to the sensitivities of aquatic biota to water level fluctuations, care must be taken in the timing of water withdrawals or fluctuations (Groen and Schroeder, 1978). Manipulation of water levels can also be used to enhance fisheries or control undesirable fish and plant species (Lantz *et al.*, 1967; Heman *et al.*, 1969). The interactions between terrestrial and aquatic ecosystems are dynamic and complex and influences, both natural and anthropogenic, can have a cascading effect on biota (Richardson *et al.*, 2002). Water level fluctuations, both natural and anthropogenic, need to be considered along with other landscape disturbances when investigating impacts to aquatic systems (Danylchuk and Tonn, 2003). In northern Canada and northern Alaska, winter roads are used to access remote communities (Government of the Northwest Territories, Department of Transportation and Transport Canada, 2003; Hinzman *et al.*, 2005), and to facilitate natural resource exploration and extraction. Large volumes of water are required for winter road construction (Adam, 1978; IORVL, 2004; Cott *et al.*, 2005; Miller, 2005). Water is often drawn

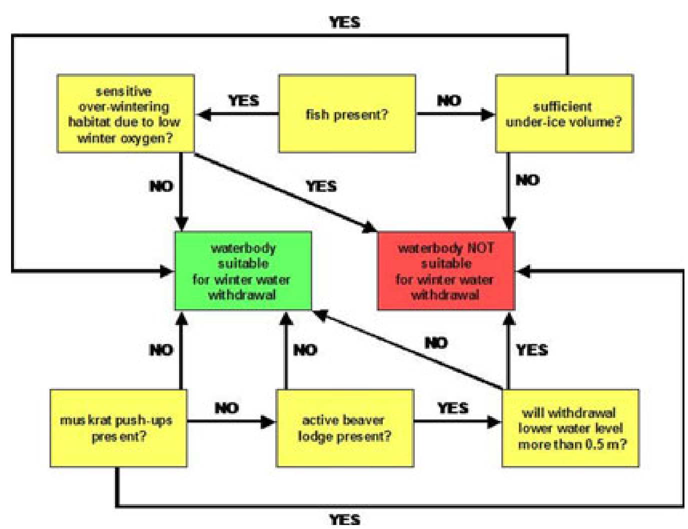

FIGURE 1. A General Decision Support System for Minimizing Risk to Overwintering Fishes and Furbearers When Selecting Water-Source Lakes for Ice Construction Applications, Such as Winter Roads. The fish, muskrat, or beaver boxes are all appropriate starting points.

from lakes that can support overwintering fish populations that can be sensitive to fluctuations in water levels (Mills *et al.*, 2002). Although water withdrawals are regulated in some jurisdictions, winter water withdrawal thresholds established to protect overwintering fishes have been largely theoretical (Cott *et al.*, 2005). A decision support system for the protection of fish and furbearers when conducting winter water withdrawal activities is presented in Figure 1. Focused research needs to be conducted to elucidate the potential impacts of water withdrawals on overwintering fishes and other aquatic organisms so reasonable winter water withdrawal thresholds can be established that, when implemented, will minimize or avoid impacts to aquatic life.

ACKNOWLEDGMENTS

The authors would like to thank Dori Miller for her assistance with proofing and formatting this manuscript, Elva Simundsson, Marge Dyck and staff at the Fresh Water Institute for assistance collecting relevant literature, Bill Morris for information regarding the Alaskan permitting processes, and to the three anonymous reviewers for the constructive feedback they provided.

LITERATURE CITED

Adam, K.M., 1978. Building and Operating Ice Roads in Canada and Alaska. Department of Indian and Northern Affairs. North of 60 Environmental Studies No. 4. Minister of Supplies and Services Canada, vi + 221.

Alasaarela, E., S. Hellsten, and P. Tikkanen 1989. Ecological Aspects of Lake Regulation in Northern Finland. In: River Basin Management–V. Advances in Water Pollution Control: A series of conferences sponsored by the IAWPRC. Pergamon Press, Inc., New York, New York, pp. 247-255.

Alexander, C.M., 1986. Impact Assessment of Extreme Drawdown on the Watauga Reservoir Fishery. Proceedings of the Annual Conference of the Southeastern. Association of Fish and Wildlife Agencies 40:15-26.

Allen, A.W., 1983. Habitat Suitability Index Models: Beaver. U.S. Fish and Wildlife Service, FWS/OBS-82/10.30 Revised, 20 pp.

Allen, A.W., 1987. Habitat Suitability Index Models: Mallard (Winter Habitat, Lower Mississippi Valley). U.S. Fish and Wildlife Service Biological Report, 82(10.132), 37 pp.

Allen, A.W. and R.D. Hoffman, 1984. Habitat Suitability Index Models: Muskrat. U.S. Fish and Wildlife Service, FWS/OBS-82/10.46. 27 pp.

Avakyan, A.B. and S.A. Podol'skii, 2002. Impact of Reservoirs on the Fauna. Water Resources 29(2):123-132.

Baker, M., Jr., 2002. National Petroleum Reserve – Alaska, 2002 Lake Monitoring and Recharge Study. Prepared for ConocoPhillips, Anchorage, Alaska, Section 1-2.

Barcia, J. and J.A. Mathias, 1979. Oxygen Depletion and Winterkill Risk in Small Prairie Lakes Under Extended Ice Cover. Journal of the Fisheries Research Board of Canada 36:980-986.

Benson, N.G. and P.L. Hudson, 1975. Effects of a Reduced Fall Drawdown on Benthos Abundance in Lake Francis Case. Transactions of the American Fisheries Society 3:526-528.

Berger, J., 1977. Northern Frontier, Northern Homeland – Mackenzie Valley Pipeline Inquiry, Vol. 2. Chapter 15. Water Withdrawal. Minister of Supply and Services Canada, Ottawa. 277.

Birtwell, I.K., S.C. Samis, and N.Y. Khan, 2005. Commentary on the Management of Fish Habitat in Northern Canada: Information Requirements and Policy Considerations Regarding Diamond, Oil Sands and Placer Mining – Summary Report. Canadian Technical Report of Fisheries and Aquatic Sciences 2607:xii + 65.

Bodaly, R.A. and L.F.W. Lesack, 1984. Response of a Boreal Northern Pike (*Esox Lucius*) Population to Lake Impoundment: Wupaw Bay, Southern Indian Lake, Manitoba. Canadian Technical Report of Fisheries and Aquatic Sciences 41:706-714.

Bonetto, A.A., J.R. Wais, and H.P. Castello, 1989. The Increasing Damming of the Parana Basin and Its Effects on the Lower Reaches. Regulated Rivers Research and Management 4(4):333-346.

Brown, K., 2002. Water Scarcity: Forecasting the Future With Spotty Data. Science 297:926-927.

Casselman, J.M., 1978. Effects of Environmental Factors on Growth, Survival, Activity and Exploitation of Northern Pike. American Fisheries Society Special Publication 11:114-128.

Casselman, J.M. and H.H. Harvey, 1975. Selective Fish Mortality Resulting From Low Winter Oxygen. Verhandlungen der Internationalen Vereinigung fur Limnologie Verhandlungen 19:2418-2429.

Coops, H., M. Beklioglu, and T.L. Crisman, 2003. The Role of Water-Level Fluctuations in Shallow Lake Ecosystems – Workshop Conclusions. Hydrobiologia 506-509:23-27.

Cott, P.A., B.W. Hanna, and J.A. Dahl, 2003. Discussion on Seismic Exploration in the Northwest Territories 2000-2003. Canadian Manuscript Report of Fisheries and Aquatic Sciences 2648:vi + 36.

Cott, P.A., D.M.A. Monita, A.R. Majewski, B.W. Hanna, and K.J. Bourassa, 2005. Application of the NWT Winter Water Withdrawal Protocol With Bathymetric Profiles of Select Small Lakes in the Mackenzie Delta Region. Canadian Manuscript Report of Fisheries and Aquatic Sciences 2731:viii + 23 + appendices.

Cott, P.A., P.K. Sibley, A.M. Gordon, R.A. Bodaly, K.H. Mills, W.M. Somers, and G.A. Fillatre, 2008. The Effects of Water Withdrawal From Ice-Covered Lakes on Oxygen, Temperature and Fish. Journal of the American Water Resources Association 41:328-342.

Cunjak, R.A., 1996. Winter Habitat of Selected Stream Fishes and Potential Impacts From Land-Use Activity. Canadian Journal of Fisheries and Aquatic Sciences 53:267-282.

Dannel, K., 1978. Intra- and Interannual Changes in Habitat Selection by the Muskrat. Journal of Wildlife Management 42(3):540-549.

Danylchuk, A.J. and W.T. Tonn, 2003. Natural Disturbances and Fish: Local and Regional Influences on Wild Fathead Minnows in Boreal Lakes. Transactions of the American Fisheries Society 132:289-298.

Davis, J.C., 1975. Minimal Dissolved Oxygen Requirements of Aquatic Life With Emphasis on Canadian Species: A Review. Journal of the Fisheries Research Board of Canada 32:2293-2332.

DFO (Department of Fisheries and Oceans), 2002. Canada's Oceans Strategy. Department of Fisheries and Oceans, Oceans Directorate, Ottawa. vi + 30 pp.

DFO (Department of Fisheries and Oceans), 2005. DFO Protocol for Winter Water Withdrawal in the Northwest Territories. Yellowknife, 3 pp.

Doudoroff, D. and D.L. Shumway, 1970. Dissolved Oxygen Requirements of Freshwater Fishes. Food and Agricultural Organiza-

tion of the United Nations, FAO Fisheries Technical Paper No. 86.
Earnst, S.L., 2004. Status Assessment and Conservation Plan for the Yellow-Billed Loon (*Gavia Adamsii*). U.S. Geological Survey, Scientific Investigations Report 2004-5258, 42 pp.
Erlandson & Associates, 2000. Oil and Gas Approvals in the Northwest Territories – Southern Mackenzie Valley. The Regulatory Roadmaps Project. Erlandson & Associates, Victoria, British Columbia.
Erlandson & Associates, 2001. Oil and Gas Approvals in the Northwest Territories – Inuvialuit Settlement Region. The Regulatory Roadmaps Project. Erlandson & Associates, Victoria, British Columbia.
Erlandson & Associates, 2002a. Oil and Gas Approvals in the Northwest Territories – Gwich'in Settlement Area. The Regulatory Roadmaps Project. Erlandson & Associates, Victoria, British Columbia.
Erlandson & Associates, 2002b. Oil and Gas Approvals in the Northwest Territories – Sahtu Settlement Area. The Regulatory Roadmaps Project. Erlandson & Associates, Victoria, British Columbia.
Evans, D.O., 2005. Effects of Hypoxia on Scope-for-Activity of Lake Trout: Defining a New Dissolved Oxygen Criterion for Protection of Lake Trout Habitat, Technical Report 2005-01. Habitat and Fisheries Unit, Aquatic Research and Development Section, ARDB, Peterborough, Ontario, 19 pp.
Evans, D.O., 2007. Effects of Hypoxia on Scope-for-Activity and Power Capacity of Lake Trout (*Salvelinus Namaycush*). Canadian Journal of Fisheries and Aquatic Sciences 64:345-361.
Fischer, P. and U. Öhl, 2005. Effects of Water-Level Fluctuations on the Littoral Benthic Fish Community in Lakes: A Mesocosm Experiment. Behavioral Ecology 16:741-746.
Flodmark, L.E.W., L.A. Vollestad, and T. Forseth, 2004. Performance of Juvenile Brown Trout Exposed to Fluctuating Water Level and Temperature. Journal of Fish Biology 65(2):460-470.
Furey, P.C., R.N. Nordin, and A. Mazumder, 2006. Littoral Benthic Macroinvertebrates Under Contrasting Drawdown in a Reservoir and a Natural Lake. Journal of the North American Benthological Society 25(1):19-31.
Gaboury, M.N. and J.W. Patalas, 1984. Influence of Water Level Drawdown on the Fish Populations of Cross Lake, Manitoba. Canadian Journal of Fisheries and Aquatic Sciences 41:118-125.
Glass, B.P., 1952. Factors Affecting the Survival of the Plains Muskrat *Ondatra Zibethica Cinnamomina* in Oklahoma. Journal of Wildlife Management 16:484-491.
Government of Canada, 1985. Fisheries Act, R.S.C., 1985, c.F-14, Amended list April 23, 1993.
Government of the Northwest Territories Department of Transportation, 2007. Road Reports. http://www.dot.gov.nt.ca/_live/pages/wpPages/roadConditions.aspx, *accessed* January 25, 2007.
Government of the Northwest Territories, Department of Transportation and Transport Canada, 2003. Transportation Infrastructure Improvements in the NWT. http://www.dot.gov.nt.ca/_live/documents/documentManagerUpload/funding_backgrounder.pdf, *accessed* January 25, 2007.
Greenbank, J., 1945. Limnological Conditions in Ice-Covered Lakes. Ecological Monographs 15(4):344-391.
Groen, C.L. and T.A. Schroeder, 1978. Effects of Water Level Management on Walleye and Other Coolwater Fishes in Kansas Reservoirs. American Fisheries Society Special Publication 11:278-283.
Hall, D.J. and T.J. Ehlinger, 1989. Perturbation, Planktivory and Pelagic Community Structure: The Consequence of Winterkill in a Small Lake. Canadian Journal of Fisheries and Aquatic Sciences 46:2203-2209.
Hecky, R.E., R.W. Newbury, R.A. Bodaly, K. Patalas, and D.M. Rosenberg, 1984. Environmental Impact Prediction and Assessment: The Southern Indian Lake Experience. Canadian Journal of Fisheries and Aquatic Sciences 41:720-732.
Heitmeyer, M.E., 1985. Wintering Strategies of Female Mallards Related to Dynamics of Lowland Hardwood Wetlands in Upper Mississippi Delta, Ph.D. Dissertation, University of Missouri, Columbia, Missouri, 378 pp.
Hellsten, S., M. Marttunen, R. Palomaki, J. Riihimaki, and E. Alasaarela, 1996. Towards an Ecologically Based Regulation Practice in Finnish Hydroelectric Lakes. Regulated Rivers: Research and Management 12:535-545.
Heman, M.L., R.S. Campbell, and L.C. Redmond, 1969. Manipulation of Fish Populations Through Reservoir Drawdown. Transactions of the American Fisheries Society 98:293-304.
Hinzman, L.D., N.D. Bettez, W.R. Bolton, F.S. Chapin, M.B. Dyurgerov, C.L. Fastie, B. Griffith, R.D. Hollister, A. Hope, H.P. Huntington, A.M. Jensen, G.J. Jia, T. Jorgenson, D.L. Kane, D.R. Klein, G. Kofinas, A.H. Lynch, A.H. Lloyd, A.D. McGuire, F.E. Nelson, W.C. Oechel, T.E. Osterkamp, C.H. Racine, V.E. Romanovsky, R.S. Stone, D.A. Stow, M. Sturm, C.E. Tweedie, G.L. Vourlitis, M.D. Walker, D.A. Walker, P.J. Webber, J.M Welker, K.S. Winker, and K. Yoshikawa, 2005. Evidence and Implications of Recent Climate Change in Northern Alaska and Other Arctic Regions. Climate Change 72:251-298.
Hinzman, L.D. and M.R. Lilly, 2004. Physical, Biological, and Chemical Characteristics of Alaskan North Slope Lakes, and Variations Due to Water Use: 2004 Update. Water and Environment Research Center, University of Alaska Fairbanks, WERC-Fact Sheet-04-01.
Hudon, C., 1997. Impact of Water Level Fluctuations on St. Lawrence River Aquatic Vegetation. Canadian Journal of Fisheries and Aquatic Sciences 57:2853-2865.
Hudon, C., 2004. Shift in Wetland Plant Composition and Biomass Following Low-Level Episodes in the St. Lawrence River Aquatic Vegetation: Looking Into the Future. Canadian Journal of Fisheries and Aquatic Sciences 61:603-617.
Hunt, P.C. and J.W. Jones, 1972. The Effect of Water Level Fluctuations on Littoral Fauna. Journal of Fish Biology 4:358-394.
IORVL (Imperial Oil Resource Ventures Limited), 2004. Environmental Impact Statement for the Mackenzie Gas Project. Calgary, Alberta, Volume 5, Section 7.
Jansen, W., 2000. Experimental Drawdown of Lake 226 in the Experimental Lakes Area, Ontario: Implications for Fish Habitat Management in Lakes and Reservoirs With Fluctuating Water Levels. Prepared for Department of Fisheries and Oceans, Central and Arctic Region, Winnipeg, March 11, 2000. 29 pp + appendices.
Järvalt, A. and E. Pihu, 2002. Influence of Water Level on Fish Stocks and Catches in Lake Võrtsjärv. Proceedings of the Estonian Academy of Sciences. Biology and Ecology 51:74-84.
Johnson, N., C. Revenga, and J. Echeverria, 2001. Managing Water for People and Nature. Science 292:1071-1072.
Juutinen, S., J. Alm, P. Martikainen, and J. Silvola, 2001. Effects of Spring Flood and Water Level Drawdown on Methane Dynamics in the Littoral Zone of Boreal Lakes. Freshwater Biology 46:855-869.
Lantz, K.E., J.T. Davis, J.S. Hughes, and J.E. Schafer, 1967. Water Level Fluctuation – Its Effects on Vegetation Control and Fish Population Management. Proceedings of the Annual Conference Southeastern Association of Game and Fish Commissioners 18(1964):483-494.
Magnuson, J.J., A.L. Beckel, K. Mills, and S.B. Brandt, 1985. Surviving Winter Hypoxia: Behavioral Adaptations of Fishes in a Northern Wisconsin Winterkill Lake. Environmental Biology of Fishes 14(4):241-250.
Magnuson, J.J. and D.J. Karlen, 1970. Visual Observations of Fish Beneath the Ice in a Winterkill Lake. Journal of the Fisheries Research Board of Canada 27:1059-1068.

McGowan, S., P.R. Leavitt, and R.I. Hall, 2005. A Whole-Lake Experiment to Determine the Effects of Winter Drought on Shallow Lakes. Ecosystems 8(6):694-708.

Messier, F., J.A. Virgl, and L. Marinelli, 1990. Density-Dependent Habitat Selection in Muskrats: A Test of the Ideal Free Distribution Model. Oecologia 84:380-385.

Miller, D.D., 2005. The Physical and Chemical Effects of Mid-Winter Pumping of Tundra Lakes on the North Slope, Alaska, MSc Thesis. University of Alaska Fairbanks, 145 pp.

Mills, K.H., S.M. Chalanchuk, D.J. Allan, and R.A. Bodaly, 2002. Abundance, Survival, Condition, and Recruitment of Lake Whitefish (*Coregonus Clupeaformis*) in a Lake Subjected to Winter Drawdown. Archiv für Hydrobiologie 57:209-219.

Nickum, J.G., 1970. Limnology of Winterkill Lakes on South Dakota. Presented at the annual meeting held in conjunction with the 32nd Midwest Fish and Wildlife Conference, North Central Division, American Fisheries Society.

Nolan, M., 2005. An Annotated Bibliography of Research Related to the Possible Long-Term Impact of Pumping Water From Tundra Ponds for the Creation of Ice Roads. Institute of Northern Engineering, University of Alaska Fairbanks, 127 pp.

Olson, M.H., S.R. Carpenter, P. Cunningham, S. Gafny, B.R. Herwig, N.P. Nibbelink, T. Pellett, C. Storlie, A.S. Trebitz, and K.A. Wilson, 1998. Managing Macrophytes to Improve Fish Growth: A Multi-Lake Experiment. Fisheries 23(2):6-12.

Paine, R.T., 1963. Trophic Relationships of 8 Sympatric Predatory Gastropods. Ecology 44(1):63-73.

Paller, M.H., 1997. Recovery of a Reservoir Fish Community From Drawdown Related Impacts. North American Journal of Fisheries Management 17:726-733.

Perry, R., 1982. Muskrats. *In*: Wild Mammals of North America, J. Chapman and G. Feldhamer (Editors). John Hopkins University Press, Baltimore, Maryland, 1147 pp.

Pierce, R.B. and C.M. Tomcko, 2005. Density and Biomass of Native Northern Pike Populations in Relation to Scale Characteristics of North-Central Minnesota Lakes. Transactions of the American Fisheries Society 134:231-241.

Pinay, G., H. Decamps, E. Chauvet, and E. Fustac, 1990. Functions of Ecotones in Fluvial Systems. *In*: The Ecology and Management of Aquatic-Terrestrial Ecotones, R.J. Naiman, H. Decamps (Editors). Man and the Biosphere Series, Volume 4, The Parthenon Publishing Group, Camforth, England, pp. 141-169.

Prowse, T.D., J.M. Buttle, P.J. Dillon, M.C. English, P. Marsh, J.P. Smol, and F.J. Wrona, 2001. Impacts of Dams/Diversions and Climate Change. *In*: Threats to Sources of Drinking Waters and Aquatic Ecosystem Health in Canada, National Water Research Institute, Burlington, Ontario, Canada. NWRI Scientific Assessment Report Series No 1. pp. 72.

Randall, D.J., 1970. Gas Exchange in Fish. *In*: Fish Physiology, W.S. Hoar and D.J. Randall (Editors). Academic Press, New York, Vol. IV, pp. 253-286.

Richardson, J.S., P.M. Kiffney, K.A. Maxcy, and K. Cockle, 2002. An Experimental Study of the Effects of Riparian Management on Communities of Headwater Streams and Riparian Areas in Coastal BC: How Much Protection is Sufficient? *In*: Proceedings From Sustainable Forest Management Network Conference "Advances in Forest Management: From Knowledge to Practice" Edmonton, Alberta, pp. 180-186.

Rigler, A.D., 1985. The Effects of an Arctic Winter on Benthic Invertebrates in the Littoral Zone of Char Lake, Northwest Territories. Canadian Journal of Zoology 63(12):2825-2834.

Ritter, L., K.R. Solomon, P.K. Sibley, K. Hall, G. Mattu, P. Keen, and B. Linton, 2001. A Review of the Sources and Pathways of Contaminants in Surface and Groundwater: A Canadian Perspective in Support of the Walkerton Inquiry. Journal of Toxicology Environmental Health Part A 65:1-142.

Rogers, K.B. and E.P. Bergersen, 1995. Effects of a Fall Drawdown on Movement of Adult Northern Pike and Largemouth Bass. North American Journal of Fisheries Management 15:596-600.

Rørslett, B., 1989. An Integrated Approach to Hydropower Impact Assessment. Hydrobiologia 175:65-82.

Rose, C.A., 2005. Economic Growth as a Threat to Fish Conservation in Canada. Fisheries 30(8):36-38.

Rosenberg, D.M., R.A. Bodaly, R.E. Hecky, and R.W. Newbury, 1987. The Environmental Assessment of Hydroelectric Impoundments and Diversions in Canada (Chapter 4). *In*: Canadian Aquatic Resources, M.C. Healy and R.R. Wallace (Editors). The Rawson Academy of Aquatic Science. Canadian Bulletin of Fisheries and Aquatic Sciences 215:71-104.

Schindler, D.M., 1998. A Dim Future for Boreal Waters and Landscapes. BioScience 48:157-164.

Slough, B.G. and R.M.F.S. Sadleir, 1977. A Land Capability Classification System for Beaver (*Castor Canadensis Kuhl*). Canadian Journal of Zoology 55(8):1324-1335.

Smith, D.W. and R.O. Peterson, 1991. Behavior of Beaver in Lakes With Varying Water Levels in Northern Minnesota. Environmental Management 15(3):395-401.

Smith, L.C., Y. Sheng, G.M. MacDonald, and L.D. Hinzman, 2005a. Disappearing Arctic Lakes. Science 308:1429.

Smith, G.R., D.A. Vaala, and H.A. Dingfelder, 2005b. Abundance of Vertebrates and Macroinvertebrates One and Two Years After a Winterkill in a Small Ohio Pond. Journal of Freshwater Ecology 20(1):201-203.

Statistics Canada, 2008. Federal, Provincial and Territorial General Government Revenue and Expenditures, for Fiscal Year Ending March 31, Annual (dollars), 1989 to 2007. CANSIM table 385-0002, http://cansim2.statcan.ca/cgi-win/cnsmcgi.pgm?Lang=E&RootDir=CII/&CANSIMFILE=CII/CII_1_E.htm, *accessed* January 9, 2008.

Stefan, H.G., X. Fang, and J.G. Eaton, 2001. Simulated Fish Habitat Changes in North American Lakes in Response to Projected Climate Warming. Transactions of the American Fisheries Society 130:456-477.

Tarver, D.P., 1980. Water Fluctuation and the Aquatic Flora of Lake Miccosukee. Journal of Aquatic Plant Management 18:19-23.

Terborgh, J., L. Lopez, P. Nunez, M. Rao, G. Shahabuddin, G. Orihuela, M. Riveros, R. Ascanio, G.H. Adler, T.D. Lambert, and L. Balbas, 2001. Ecological Meltdown in Predator-Free Forest Fragments. Science 294:1923-1926.

Thorp, J.H. and A.P. Covich, 1991. Ecology and Classification of North American Freshwater Invertebrates. Academic Press, San Diego, California, 911 pp.

Townsend, G.H., 1975. Impacts of the Bennett Dam on the Peace-Athabasca Delta. Journal of the Fisheries Research Board of Canada 32:171-179.

Turner, M.A., D.B. Huebert, D.L. Findlay, L.L. Hendzel, W.A. Jansen, R.A. Bodaly, L.M. Armstrong, and S.E.M. Kasian, 2005. Divergent Impacts of Experimental Lake-Level Drawdown on Planktonic and Benthic Plant Communities in a Boreal Forest Lake. Canadian Journal of Fisheries and Aquatic Sciences 62:991-1003.

Verrill, D.D. and C.R. Berry, 1995. Effectiveness of an Electrical Barrier and Lake Drawdown for Reducing Common Carp and Bigmouth Buffalo Abundances. North American Journal of Fisheries Management 15:137-141.

Welch, H.E. and J. Kalff, 1974. Benthic Photosynthesis and Respiration in Char Lake. Journal of the Fisheries Research Board of Canada 31:609-620.

Wetzel, R.G., 2001. Limnology. Lakes and Rivers Ecosystems (Third Edition). Academic Press, San Diego, California, 1006 pp.